Superconducting Transformer Failure: Testing and Investigation

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***Abstract*—A partial core superconducting transformer, that was built in the Electrical and Computer Engineering Department, was tested under no-load, short-circuit, full-load and a two minute full-load endurance run. The first no-load, short-circuit and full load tests were only partially successful because the accuracy of the meters were not satisfactory enough to confirm the mathematical models. The transformer failed the endurance run; voltage dipping and rapid liquid nitrogen boil-off was observed one minute and a half into the test. An investigative approach was taken to determine the cause of the failure. The radial field at ends of the partial core, was determined not to have caused the tape to go out of its superconducting state. An open circuit test was performed on one of the outside winding which led to the discovery of a shorted turn. The windings and insulation of the transformer were taken apart to visually observe the faulty turns.**

I. Introduction

A 15kVA Bismuth-Strontium-Calcium-Copper-Oxide (BSCCO) superconductor partial core transformer [1] was retested to confirm mathematical models for the core and superconductor. The transformer was operated under no-load, short-circuit and full load conditions, and then subjected to a full load endurance run.

II. Transformer Description

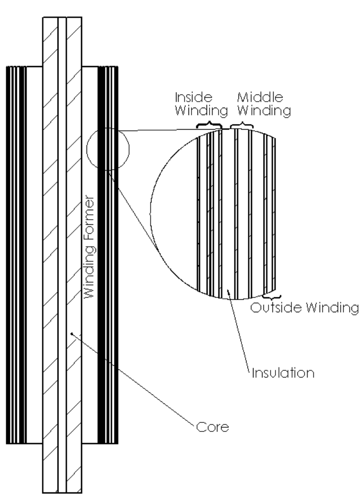


Fig. 1. The partial core superconducting transformer.

Fig. 2. The transformer inside the cryostat

Figures 1 and 2 and Table I show the transformer and its specifications. The superconducting transformer consisted of three windings. The inside winding was rated for 230V and both the middle and outside windings rated for 115V. The middle and outside windings were connected in series, in effect making it a 230V/230V isolating transformer (Figure 3). The rated current of the transformer was 65A on all the windings.

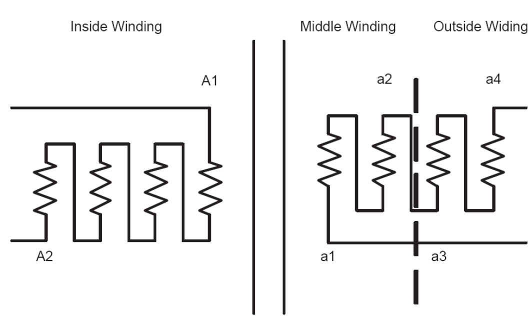


Fig. 3. Winding configuration; Primary Winding:A1-A2, Secondary Winding: a1-a4

TABLE I
TRANSFORMER SPECIFICATIONS

Core Specifications		
Lamination Thickness	0.23	mm
Stacking Factor	0.96	
Operating Temperature	-50	°C
Core Length	484	mm
Core Outer Radius	40	mm
Core Inner Radius	8.2	mm

Winding Specifications		
Radial Width	0.3	mm
Axial Height	4.65	mm
Operating Temperature	-196	°C
Length	384	mm
Layer Insulation Thickness	0.2 - 3.45	mm
Number of Layers:		
- Inside Winding	4	
- Middle Winding	2	
- Outside Winding	2	
Total number of layers	8	
Conductor Material	Bi-Sr-Ca-Cu-O	

The windings of the transformer were made out of BSCCO superconducting tape. This is a Bismuth based, multi-filamentary, high temperature superconductor ceramic encased in a silver alloy matrix. There were four layers in the primary winding and two layers for each secondary winding. The windings were insulated with Nomex tape as well as Nomex paper between the layers.

The transformer core is made out of 0.23mm thick cold-rolled grain oriented steel laminations. There is only a central core; there are no limbs or yokes. The design of this partial core was to minimize weight as well as core losses. The core is isolated from the liquid nitrogen by a vacuum and two layers of fibreglass. There are 434 laminations and the core length is longer than the winding height of the transformer. This is to reduce perpendicular flux on the ends of the windings. The perpendicular flux decreases the critical current of the tape and must be reduced as much as possible.

The partial core transformer was operated at liquid nitrogen temperature, with the transformer windings immersed in the liquid nitrogen inside a cryostat (Figure 2). The cryostat has a vacuum chamber separating the core and the windings, as well as another vacuum chamber separating the outside atmosphere and the windings which were immersed in liquid nitrogen. The vacuum chambers are designed to insulate the liquid nitrogen as well as isolating the partial core and operating it at room temperature. The two vacuum chambers also contain insulating tissue to minimize heat transfer via convection and reflective mylar which minimizes heat transfer via radiation from the outside to the inside.

III. TESTING

The open-circuit, short-circuit, full-load and a two minute full-load endurance run were performed on the transformer with the primary voltage applied on the inside winding. The first three tests were partially successful; the results of these tests are shown in Table II. The open-circuit test (Table IIa) shows a voltage ratio of 0.98 indicating near perfect coupling of the flux to both primary and secondary windings. The short-circuit test (Table IIb) gives a current ratio of 1.02 which shows that despite the partial core, very little current is diverted into magnetisation. The loaded test (Table IIc) indicates an efficiency of 100% and a voltage regulation of 3.2%. However, the losses of the transformer are less than the resolution of the instrumentation used to measure the power. This can be seen in the time series data downloaded from the meter (Figure 4). The inaccuracy is mainly due to the transducer used to measure the current.

The conclusion that can be drawn from this is that the core and winding losses were less than 270W. The open-circuit and short circuit test showed consistent results with the model but has the same resolution problem as the full load test. The low value of regulation mean that these types of transformer may not need on-load tap changers to operate within specification, from no-load to full load.

TABLE II
TEST RESULTS FOR THE SUPERCONDUCTING TRANSFORMER.

Open Circuit Test		
Primary Voltage	230.84	V
Secondary Voltage	226.18	V
Primary Current	20	A
Primary Real Power	0.2	kW
Primary Apparent Power	4.7	kVA

(a)

Short Circuit Test		
Primary Voltage	25.45	V
Primary Current	66	A
Primary Real Power	0.1	kW
Primary Apparent Power	1.7	kVA
Primary Power Factor	0.06	

(b)

Loaded Test		
Primary Voltage	230.90	V
Primary Current	65	A
Primary Real Power	13.8	kW
Primary Apparent Power	15.1	kVA
Primary Power Factor	0.92	
Efficiency	100	%
Secondary Voltage	223.56	V
Secondary Current	61	A
Secondary Real Power	13.8	kW
Secondary Apparent Power	13.8	kVA
Secondary Power Factor	1.00	
Regulation	3.2	%

(c)

A. Transformer Failure

The full-load endurance run was commenced with the transformer at rated voltage and load. The failure occurred 1 minute and 35 seconds into the full-load endurance. It was observed that the outside winding voltage decreased at a very fast rate and there was rapid liquid nitrogen boil off. This caused a rapid increase in pressure and popped one of the vents

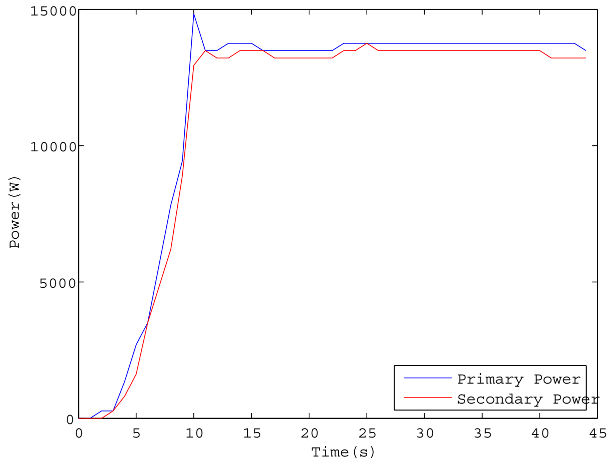


Fig. 4. Primary and secondary winding full load test power readings from the Fluke 434.

on top of the transformer. The circuit breaker was quickly opened to remove the applied voltage. All the safety valves were opened to relieve the pressure and it was observed that a lot of nitrogen gas escaped. The inside winding was found to be open circuited which indicated that the whole/part of the winding had been damaged.

IV. Failure Investigation

There are several reasons for the winding to fail during the full-load endurance run. The winding could have gone out of its superconducting state due to not having enough cooling and exceeding the critical temperature. The radial flux, caused by having a partial core, could have lowered the critical current below the full load current that was flowing in the winding. The radial flux could also cause eddy currents in the silver lattice and stainless steel which might have heated the superconductor and cause it to quench. A manufacturing or process defect could have appeared in the silver lattice or the BSCCO ceramic, giving a section that was more resistive than the good superconductor, and hence the faulty section could melt during testing.

For the radial flux component, there is no physical measurement that could be done as the gap between the winding is too small for any measuring equipment, and also the winding could no longer be energized. There are only simulations and approximations to the magnitude of the radial flux component that could be obtained. By using Finite Element Modelling[2] and the Magnet program, a flux plot which describes the magnitude and direction was generated (Figure 5).

The peak magnitude of the flux as indicated by Magnet was 0.03T at right-angles to the tape plane on the first turn at the ends of the inside winding. The critical current is lowered due to this radial flux and is modelled by Oomen et al[3]. The formulas described in Oomen et al were obtained via empirical studies on a 1MVA Siemens railway transformer in Germany. The critical current of the superconducting tape is influenced by the direction and magnitude of the applied magnetic field, temperature and the characteristic self-field. The DC critical current is described by Equation 1.

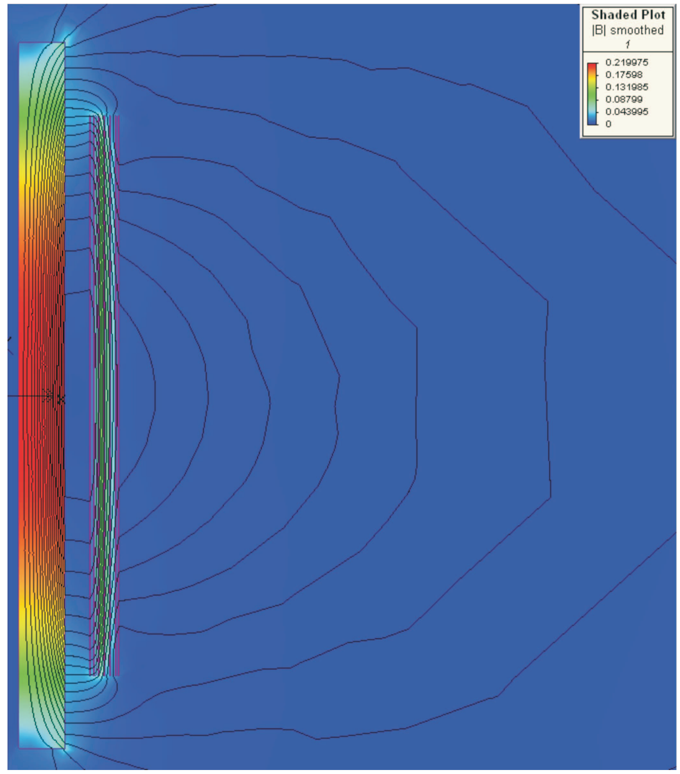


Fig. 5. Flux plot of the superconducting transformer under full load conditions.

$$I_c(T, B, \Theta) = \frac{I_{c0,77}(3.69 - 0.035T)}{1 + \mid \frac{Bsin(\Theta)}{B_0(T)} \mid^{\alpha(T)}} \quad (1)$$

where,

$I_{c0,77}$	=	Rated critical current at self-field
B	=	Magnetic field strength inside the superconducting tape
Θ	=	Magnetic field angle with respect to the superconducting tape plane
T	=	Temperature of the superconductor

The characteristic magnetic self-field, B_0, is given by the fitted formula:

$$B_0 = 0.03 + (0.0032 - 0.0000393T)I_{c0,77} \quad (2)$$

The exponent function in equation 1, $\alpha(T)$, is given by:

$$\alpha(T) = 0.2116 + 0.0083T + (0.0012 + 0.00003T)I_{c0,77} \quad (3)$$

Using Equation 1, the critical current was lowered to 79.03A from its 120A nominal rating. The input current waveform only spends 6 milliseconds per cycle above 79.03A (Figure 6).

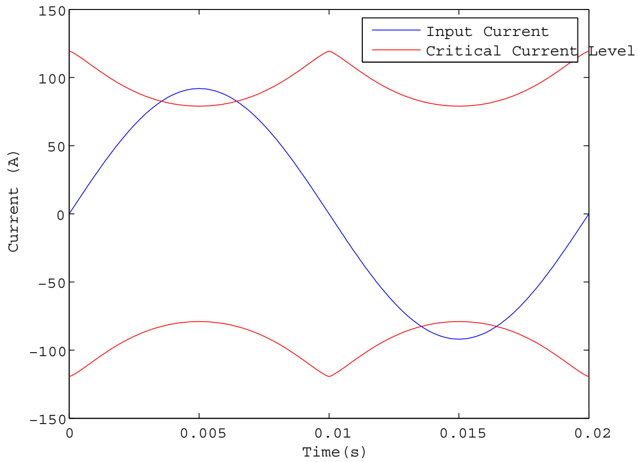
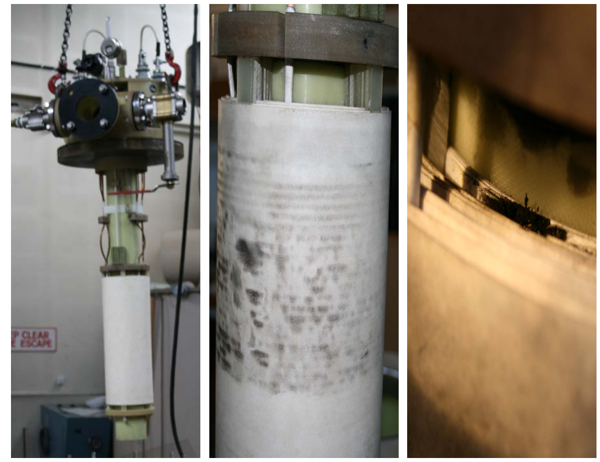


Fig. 6. The input current waveform of the superconducting transformer exceeding the critical current level calculated in equation 1.



(a) (b) (c)

Fig. 7. Damage caused to the superconducting transformer during full-load endurance run;(a) before full-load endurance run failure, (b) contaminants sticking onto the insulation after transformer failure and (c) insulation burn damage from the blown superconductor.

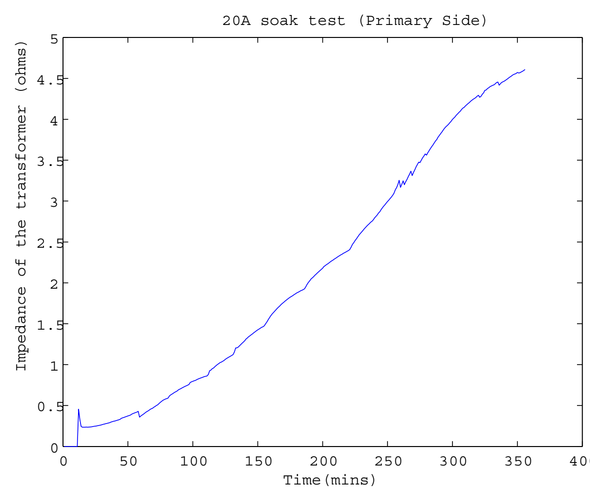


Fig. 8. Transformer impedance during the 6 hour 20A endurance run

Superconductors do not instantaneously go into the quenched state. Heinrich et al [4] did several experiments to obtain optical observations on the quench effects of YBCO superconductor. According to Heinrich, it took 1.1ms for the YBCO to quench and fully generate liquid nitrogen bubbles (boil-off) 7.7ms after quenching occurs. In Zhou et al [5], BSCCO superconductor was forced to quench under short-duration high-current pulses. Zhou et al also showed that the quenching current drops significantly as the period of the pulses lengthen. Zhou et al showed that the superconductor has a combined quench and recovery time of less than 1ms. However, the input current applied in our transformer winding was not high enough above the critical current to achieve the same effects as in Heinrich's and Zhou's experiments. In both papers, the current applied was 1.5 times greater than the rated critical current.

The transformer windings were then taken out of the cryostat for investigation (Figure 7). Figure 7(c) shows burnt out insulation which indicates that a small section of superconductor has burnt and open circuited the winding. Contaminant marks on the insulation are also observed in Figure 7(b). The carbon scorches and ring marks, due to combustion, gives evidence of the presence of oxygen. With the transformer submerged in liquid nitrogen, some of the oxygen from the atmosphere could have been condensed into liquid form creating a liquid nitrogen and oxygen mix. Another source of oxygen could be from the air voids in the insulation or air bubbles trapped between the insulation and the windings. The air winding chamber was not evacuated, only displaced by the liquid nitrogen when filling. This suggests that the transformer should have had the air evacuated from the chamber prior to filling.

Looking at the construction of the transformer, the windings and insulation were packed tightly together. It did not have any cooling channels for liquid nitrogen in between the windings. Unfortunately there were no temperature readings for the inside windings when the tests were done.

An open circuit test was performed on the outside winding. During this test, it was observed that the current rose dramatically. An applied voltage of 8V resulted in 20A of current drawn in the outside winding. It was also observed that the middle winding was producing 8V which indicated proper voltage transformation. This indicated shorted turns somewhere in the transformer and given that the inside winding had already been damaged, it was highly possible that the inside winding has shorted turns.

The transformer was then subjected to a 6 hour 20A endurance run, open circuit on the outside winding, in an attempt to measure the temperature at the surface and both ends of the windings. The temperature readings showed that the transformer was fully submerged in liquid nitrogen throughout the entire endurance run. The open circuit current reading showed a decaying transient over time, the voltage had to be stepped up to maintain the current near 20A.

The resulting impedance from these readings shows that it steadily increased over time (Figure 8). At the end of the 6 hour test, it was visually observed that the liquid nitrogen was boiling off at a faster rate compared to that at the beginning of the test. This indicates that the shorted turn is no longer superconducting and the silver metal matrix was slowly heating up hence increasing the overall transformer impedance.

V. Transformer Unwinding

(a) (b) (c)

Fig. 9. Transformer winding burns (a)outer layer of the middle winding, (b)outermost layer of the inside winding and (c)innermost layer of the inside winding.

The transformer windings and insulation were taken apart to visually inspect the faulty turn(s). Two layers of the outermost winding (secondary winding) were found unharmed, only superficial damage (Figure 7(b)) appeared on the surface of the Nomex paper insulation. The first signs of winding damage appeared on the outer layer of the middle winding (Figure 9(a)). Melted glue residue was found on the insulation which indicates that the windings heated the Nomex tape glue to boiling point. The damage to the transformer got worse as more windings and insulation were removed. The Nomex tape on the superconductor on the outermost layer of the inside winding was completely burnt (Figure 9(b)). Figure 9(c) shows a whole section of superconductor that has been warped due to expansion and contraction. The ends of the innermost layer of the primary winding were burnt and disconnected, evidence of carbon suggests that combustion was the cause.

The damage appeared mostly around the center of the inside and middle windings, which suggests that the windings were packed too tightly together to allow sufficient cooling. The ends of the windings were relatively unscathed due to it being exposed directly to liquid nitrogen. This indicates that the superconductor in the inside of the innermost layer quenched due to the temperature rise. A cascading effect ensues which led to the superconductor burning and disconnecting the primary layer. Further heating caused insulation damage on the outer layers of the inside and middle windings. Figure 10 shows the resultant damage on the winding former. The damage appears to be superficial and the vacuum chamber is still intact.

Fig. 10. Damage on the winding former

VI. Conclusion

The results of the failure investigation were presented and the likely cause of the failure was determined. The Magnet simulation indicates that the radial flux was insufficient in lowering the critical current for the superconductor to quench. Further testing indicated that the inside winding had a shorted turn. The windings and insulation were then removed and a visual inspection commenced. There was substantial damage caused to the middle and inside windings, the burn profile indicates that the superconductor quenched due to lack of cooling. The inside winding went out of superconducting state which then cause the winding to fuse and burn out. The resultant heat caused further damage to the subsequent outer layers as well as the middle winding.

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